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Article

Robust Optimal Operation Strategy for a Hybrid Energy System Based on Gas-Fired Unit, Power-To-Gas Facility and Wind Power in Energy Markets

Masoud Agabalaye-Rahvar ¹, Amin Mansour-Saatloo ¹, Mohammad Amin Mirzaei ¹, Behnam Mohammadi-Ivatloo ^{1,2,*}, Kazem Zare ¹ and Amjad Anvari-Moghaddam ^{2,*}

¹ Faculty of Electrical and Computer Engineering, University of Tabriz, 5166616471 Tabriz, Iran; m.agabalaye97@ms.tabrizu.ac.ir (M.A.-R.); amin_mnsr97@ms.tabrizu.ac.ir (A.M.-S.); aminmirzaei780@gmail.com (M.A.M.); kazem.zare@tabrizu.ac.ir (K.Z.)

² Department of Energy Technology, Aalborg University, 9220 Aalborg, Denmark

* Correspondence: bmohammadi@tabrizu.ac.ir (B.M.-I.); aam@et.aau.dk (A.A.-M.)

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Abstract: Gas-fired power units (GFUs) are the best technology in recent years due to lower natural gas prices, higher energy transformation performance, and lower CO₂ emission, as compared to the conventional power units (CPUs). A permanent storage facility called power-to-gas (P2G) technology can provide adaptation of ever-increasing renewable energy sources (RESs) fluctuations in power system operations, as well as reduce dependency to buy natural gas from the gas network. High investment and utilization expenditures of state-of-the-art P2G technology do not lead to economically effective operation individually. Therefore, in the present paper, an integrated GFUs-P2G-wind power unit (WPU) system is proposed to determine its optimal bidding strategy in the day-ahead energy market. A robust optimization approach is also taken into account to accommodate the proposed bidding strategy within the electricity price uncertainty environment. This problem was studied by using a case study that included a P2G facility, GFU, and WPUs to investigate the effectiveness and capability of the proposed robust bidding strategy in the day-ahead energy market. Simulation results indicate that the obtained profit increase by introducing the integrated energy system, and the P2G facility has a significant effect on participating GFUs, which have gas-consumption limitations in order to achieve maximum profit. Moreover, as it can be said, the amount of purchased natural gas is decreased in the situations, which do not have any gas-consumption limitations. Furthermore, the proposed system's operation in the robust environment provides more robustness against electricity price deviations, although it leads to lower profit. In addition, deploying P2G technology causes about 1% incrementation in the introduced system profit.

Keywords: highly flexible gas-fired power units (GFUs); day-ahead energy market clearing; power-to-gas conversion technology (P2G); integrated optimal bidding strategy; wind power unit (WPU); robust optimization approach

1. Introduction

In the last few years, some technical and environmental aspects have encouraged researchers to utilize the novel high-flexible facilities in power system operations. Gas-fired power units (GFUs) and power-to-gas (P2G) conversion technology are two of those facilities. GFUs are preferred in the integrated electricity and natural gas systems instead of conventional power units (CPUs) due to lower natural gas prices, higher energy transformation performance, and lower air pollutant emission [1–3].

Besides this, GFUs are one of the promising solutions to prepare the regulation services for the power systems with the penetration of renewable energy sources (RESs) [4]. P2G technology is a system that could convert electric power into natural gas and has released energy between electricity and natural gas systems [5]. This novel technology is called a permanent P2G storage facility, which can accommodate the fluctuations of ever-increasing RESs in power system operations besides preparing regulation services utilizing quickly available electrolysis [6]. So far, P2G technology has not been provided individually with an economically effective operation in various energy systems, causing high investment and utilization expenditures.

Different technical methodologies are considered to obtain the optimal operation of integrated electricity and natural gas systems and improve the efficiency of electrical energy [7]. All of these methods are constructed as a framework based on multi-stage optimization programming to optimize the energy flows in the integrated energy systems [8,9]. Organizing the secure connection between electricity and natural gas systems establishes several profits for various system sectors, such as utility, customers, and network operators [10–12]. To this end, the energy hub (EH) concept has emerged to meet the electrical, thermal, and gas demands in an optimal economic–environmental procedure [13]. Conversion energy devices are the essential facilities in the EH systems to supply demands in different situations by constituting an optimal connection between several infrastructures. Thus, P2G conversion technology and high-flexible GFU are employed to reduce the total operation cost and increment the energy efficiency [14,15]. From these perspectives, more related researches have been accomplished in the investigated literature.

Most of the works that have been investigated fall into the two main categories. The first category is modeling and investigating various bidding strategies of generation companies (GenCos) with different objectives and methodologies. The uncertainties of the electricity price market and outage of GenCos, which impacts profit, are handled in Reference [16] through the information gap decision theory (IGDT). The uncertainty of day-ahead electricity price is modeled via applying IGDT in Reference [17], to determine the combined bidding strategy of GenCos and demand response aggregator (DRA). Thus, the obtained optimal results of the proposed problem in Reference [17] have been confirmed after the realization of market prices. In Reference [18], a novel teaching–learning-based optimization (TLBO) method was introduced to solve GenCos and major consumers' bidding strategies in the day-ahead electricity market. In the deregulated electricity market, as covered in Reference [19], knowing the rival GenCos is helping to gain maximum benefit, which is performed by a grey wolf optimizer (GWO) algorithm. Another meta-heuristic solution called whale optimization algorithm (WOA) was proposed in Reference [15], to obtain the maximum profit by determining the optimal bidding strategy. Moreover, the authors of Reference [20] have taken into account the IGDT procedure to distinguish the risk-averse or risk-taker of bidding strategy for price-taker GenCos in the uncertain conditions day-ahead energy and reserve electricity markets. The authors of Reference [21] presented a robust framework for micro EH (mEH) combined with gas-fired GenCos with analyzing the impacts of integrated demand-response program (IDR) and hydrogen storage system (HSS) technologies. In Reference [22], a renewable-based power generation multi-objective robust scheduling methodology was presented, to lessen the effects of uncertainties on the proposed system's stable operation. A bi-level hierarchical decision-making was published in Reference [23], to specify the character of DRA and GenCos bidding strategy on the adaptability of loads. An upper level of the proposed problem in Reference [23] is minimizing generation costs, as well as the cost of demand curtailment. Meanwhile, the lower level aims at determining the optimal demand response (DR) quantity and prices of demand curtailment from various aggregators.

The second category of analyzed works is related to the effects of P2G conversion technology on the integrated energy systems. In Reference [2], a best-coordinated optimal scheduling tool between integrated power and natural gas networks (IPGNs) equipped with a P2G facility was represented. Moreover, a market equilibrium-based game theory model was presented in Reference [2], to study these effects on the optimal dispatch of IPGNs. The linearized constraints of both electricity and

natural gas systems were constructed in Reference [3], in which the impacts of deploying P2G facilities on daily economic scheduling were investigated. Moreover, Reference [24] focused on the risk-averse approach, which was modeled as an improved conditional value at risk (CVaR) to handle the uncertainty associated with wind and solar power units. A two-stage robust scheduling method was introduced in Reference [25] for the IPGNs equipped with P2G and hydrogen compressed natural gas (HCNG) technologies, to decrease operational risk and increase the system's stability in the worst cases. In Reference [26], a two-stage multi-objective stochastic unit-commitment approach was proposed for IPGNs, in which flexible energy devices as P2G facility and DR are embedded to lessen the environmental gas emissions and operating costs. The optimal scheduling structure of an EH was reported in Reference [27]; it was equipped with GenCos and multi-carrier energy storage systems, i.e., a P2G system, in order to demonstrate the effectiveness of the P2G system on the operation costs. In Reference [15], the valuable outcomes of the P2G facility and compressed air energy storage (CAES) system on reducing the RESs' intermittency and operation costs of the proposed EH were indicated. In addition to the RESs' uncertainty, the fluctuations of the electricity prices and various demands were considered in Reference [15], where CVaR was utilized to analyze the risk of the introduced strategy. A probabilistic optimal scheduling framework of a viable P2G-based IPGNs was presented in Reference [28], in which load shifting-based DR programs were taken into account. In Reference [29], a probabilistic power flow methodology was established for IPGNs coupled with the P2G system and wind power, and it indicated that the P2G system decreases the impacts of wind power on the security of the power system. In Reference [14], a hybrid bi-level IGDT-stochastic co-optimization framework for IPGNs was proposed, in which gas demand, electrical demand, and wind-power generation were considered as uncertain parameters.

All of the related research works we investigated in the literature review are associated with the optimal bidding strategies of GenCos and the impacts of the P2G facility on the integrated electricity and natural gas systems, which are proposed with various objectives and solution approaches. However, all of those researches are mainly about the optimal scheduling and bidding frameworks without extra wind-power utilization. Thus, according to this issue, there is no focus on the P2G conversion facility's bidding strategy in the integrated electricity and natural gas networks. This topic is the research gap of the analyzed works. To this end, in this paper, a coordinated optimal bidding strategy of hybrid energy system coupled with GenCos and P2G conversion technology and also with wind power unit (WPU) is proposed to participate in the day-ahead energy market. Applying the P2G facility in the combined manner has a significant impact on producing electric power of GFUs with considering gas-consumption limitations in order to participate in the energy market. In addition to obtaining a realistic and accurate optimal bidding strategy, the electricity market price's uncertainty is handled via the robust optimization technique. A review of the exitance work portfolio is provided in Table 1. Briefly, the main contributions of this paper are summarized as follows:

1. Introducing a large-scale P2G conversion technology to handle the gas-consumption limitation of GFUs.
2. A risk-based method is considered to handle the day-ahead electricity-market-price uncertainty in the scheduling problem.
3. An optimal bidding strategy for a hybrid energy system coupled with GFU-P2G-WPU facilities is proposed to participate in the day-ahead energy market.

The rest of this paper is organized as follows. Section 2 describes the mechanism and energy contribution of permanent energy storage, i.e., a P2G conversion facility. The proposed problem formulation is indicated in Section 3. The numerical results and analysis of two case studies are introduced in Section 4, to represent the capability and effectiveness of the considered optimal bidding strategy for a hybrid energy system. Finally, Section 5 concludes and reports noticeable outcomes.

Table 1. Comparison of the literature.

| Reference | Bidding Strategies of GenCos | Technologies | | | Uncertainty Management |
|--------------|------------------------------|--------------|-----|-----|------------------------|
| | | GFU | WPU | P2G | |
| [16] | ✓ | ✓ | | | IGDT |
| [17] | ✓ | ✓ | | | IGDT |
| [18] | ✓ | ✓ | | | IGDT |
| [19] | ✓ | ✓ | | | Deterministic |
| [25] | ✓ | ✓ | ✓ | | Robust |
| [1] | ✓ | ✓ | | ✓ | Stochastic |
| [24] | ✓ | ✓ | | ✓ | Stochastic |
| Current work | ✓ | ✓ | ✓ | ✓ | Robust |

2. Research Background

2.1. Mechanism of Power-To-Gas System (P2G)

The novel P2G conversion system has emerged in recent years. Researchers and system operators (SOs) are also very willing to deploy this renewable-based energy-storage system, the so-called P2G conversion facility, in integrated electricity and natural gas systems [14,15]. However, before utilizing the P2G facility in various networks, perfect recognition of its process will help deploy efficiently and reduce operating costs.

Two main processes exist in generating synthetic natural gas (SNG), namely electrolysis and methanation. At first, delivering electricity from the energy market or wind power unit to the P2G system splits water into hydrogen and oxygen via the electrolysis process indicated in (1). Therefore, the generated hydrogen reacts with carbon dioxide (CO₂), according to the methanation procedure, to produce SNG described in (2), which is known as the Sabatier reaction. The Sabatier reaction is mainly performed by using chemical catalysts, in which the most common catalyst is nickel with aluminum oxide [30]. Until today, some of the practical projects have used catalytic methanation, such as CO₂-SNG, in Poland [31]; Jupiter, in France, with the capacity up to 1000 kW [32]; Exytron demonstration project in Germany, with the capacity of 21 kW [33]; etc. Moreover, this reaction can be conducted with a standard metabolic procedure in the production of biogas, and biological reactors can be taken into account [34]. The Power to Flex joint project in Germany and the Netherlands [35], Symbio in Denmark [36], and Wijster in the Netherlands [37] are a examples of practical projects that have used biological reactors. The optimal condition to perform the reaction is 10 bar pressure and 300 °C, which, in doing so, over 98% CH₄ can be produced [34]. Furthermore, the required CO₂ can be available from many sources, e.g., biogas, refineries, fuel oil, etc.; however, biogas is the best source for the P2G procedure [38]. As depicted in References [39,40], these two presented processes are principle steps in progressing the P2G system, which is illustrated in Figure 1. The energy conversion efficiency of the whole P2G system mostly about between 50% and 60%. However, producing hydrogen from the first stage of SNG is more productive than the whole P2G procedure.



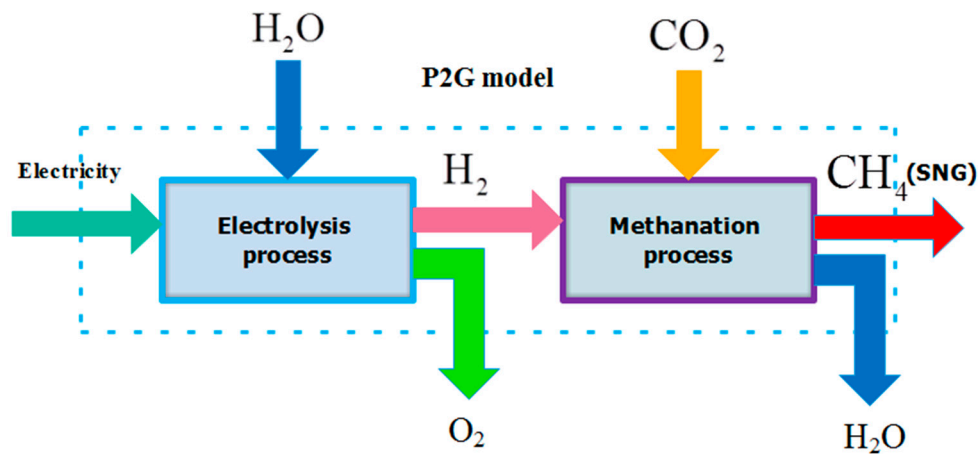


Figure 1. Synthetic natural gas (SNG) production process via P2G technology model.

2.2. P2G Contribution to Energy Supply

Although hydrogen produced from the first stage of the P2G process is more efficient than generating SNG, the employment of hydrogen is restricted to fuel cells in some specified industries. SNG generated has the capability to be used in the GFUs, and it also has other considerable applications to improve the operational flexibility of P2G and GFUs facilities. Furthermore, SNG has comparable properties to conventional natural gas (CNG), which can be gathered, transferred, and sold to the natural gas network. Thus, in general conditions, SNG is more realistic, and the P2G conversion facility is regarded in the present paper.

P2G conversion technology has considerable trading opportunities despite its not-ideal conversion efficiency. Moreover, the cross-product arbitrage is implemented by P2G technology between electricity and natural gas networks. P2G technologies can benefit more from the energy trade when the price gap between the electricity and gas markets is significant. Additionally, the represented facility can achieve profit by participating in reserve markets by deploying rapid active proton exchange membrane (PEM) electrolysis [41].

2.3. P2G Trends in the World

Due to the contribution of RESs around the world, the significance of deploying a large-scale energy storage system was discussed in recent publications [42–44]. Thus, the installation and application of P2G technology, which is driven by the growing part of WPU and solar energies, are attracting interest, especially in Europe [45–47]. In addition, there are a lot of P2G research projects that have been done or are ongoing, for instance, in Switzerland, Denmark, Japan, and France. On the other hand, the investigation of various effects of P2G applications is considered in References [48,49], from energy-economics and climate-problem aspects. These analyses are related to the integrated energy systems [2], energy hubs [50], microgrids [51], and multi-carrier energy systems [52].

3. Problem Description

The current research is about the optimal bidding strategy of the hybrid energy system. Thus, P2G technology should be considered, besides the other facilities to create introduced infrastructure. The WPU's curtailed and non-dispatched power is converted to natural gas via the P2G process, according to Relations (1) and (2). Gas storage system (GSS) charges with the produced natural gas in off-peak times and discharges to supply GFU's input energy in peak and required hours. By these explanations, the daily gas-fuel-consumption limitation is eliminated, and the GFU can generate power upon to its nominal capacity. It can be stated that the P2G facility's role in providing better situations to contribute GFU in the energy market, which could be called backup facilities, is so highlighted. The summation of power productions by GFU and WPU is transferred to the energy

market concerning the line's maximum capacity. Therefore, the presented hybrid energy system, with a demonstration of different coupling facilities, is indicated in Figure 2.

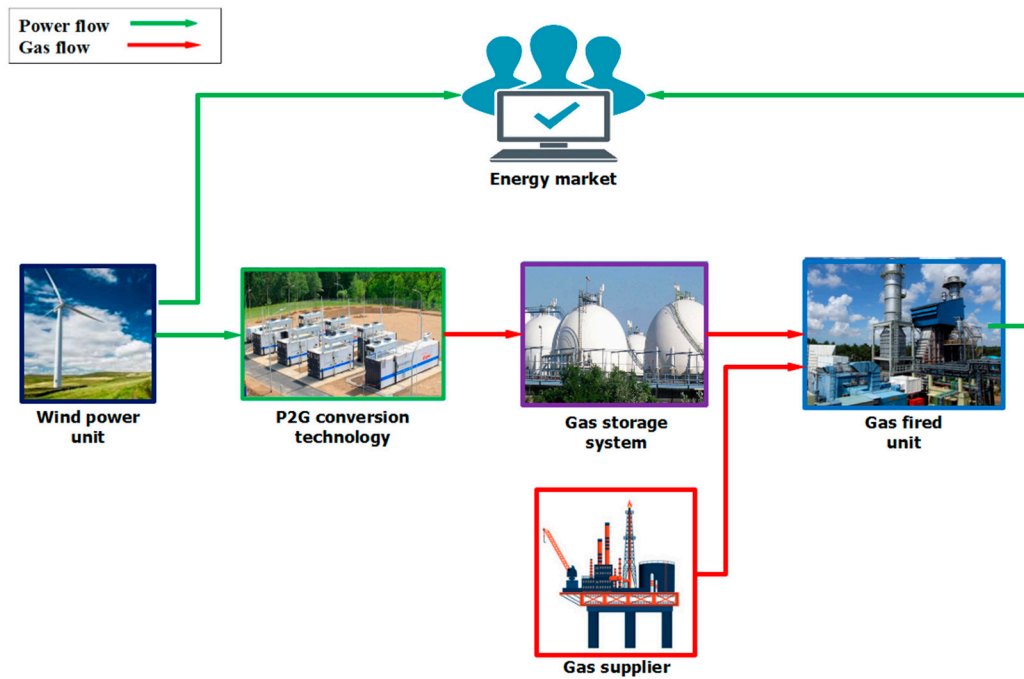


Figure 2. The proposed hybrid energy system with coupling facilities.

4. Problem Formulation

4.1. Objective Function

All units' offers related to the hybrid energy system for all hours of the next day are submitted to the day-ahead energy market. According to the cleared day-ahead electricity market price and gas-fuel-consumption limitation, the proposed hybrid system's maximization profit problem is accomplished in (3). Hence, the hybrid energy system's income is included in four parts. The first part of Equation (3) relates to the revenue acquired from selling electric power of GFU and WPU facilities into the day-ahead energy market. The second part corresponds to the operation cost of GFUs, in which these units have daily gas-fuel-consumption limitations. The charging and discharging expenditures of a gas storage system (GSS) are indicated in the third part and the last term of the objective function associates with the cost of producing SNG by consuming electric power via the P2G conversion technology. It is worth mentioning that the gas produced from P2G technology is equivalent to the amount of gas in the charging mode of GSS. The clear identification and explanation of several terms relevant to the objective function is provided in (4).

$$\text{Max} \left\{ \sum_{t=1}^{NT} \left[\lambda_t^E (P_t^{WT} + P_t^{GF}) - \lambda_t^G (F_t^{GF} (P_t^{GF})) - \sum_{k=1}^{NGS} [C_{k,t}^{ch,GSS} (G_{k,t}^{ch,GSS}) + C_{k,t}^{dis,GSS} (G_{k,t}^{dis,GSS})] - \sum_{p=1}^{NP} [C_{p,t}^{P2G} (G_{p,t}^{P2G})] \right] \right\} \quad (3)$$

$$O.F. = \text{Max} \left[\begin{array}{l} \text{(Total energy sold profit)} - \text{(Operation cost of GFU)} \\ \text{(Charge and discharge costs of GSS)} - \text{(SNG cost)} \end{array} \right] \quad (4)$$

4.2. Problem Constraints

4.2.1. Forecasted Wind Power

In order to solve the maximization profit problem, all constraints of considered facilities and the connections between them should be taken into account. According to the forecasted wind-speed data and some technical limitations, such as cut-in speed and cut-out speed, Constraint (5) is utilized to calculate the forecasted electric power of WPU.

$$P_t^{FWT}(v_t^{WT}) = \begin{cases} 0 & ; \quad v_t^{WT} < v^{CI} \\ P^{WT,R} \left(\frac{v_t^{WT} - v^{CI}}{v^{WT,R} - v^{CO}} \right)^3 & ; \quad v^{CI} \leq v_t^{WT} < v^{WT,R} \\ P^{WT,R} & ; \quad v^{WT,R} \leq v_t^{WT} < v^{CO} \\ 0 & ; \quad v_t^{WT} \geq v^{CO} \end{cases} \quad (5)$$

4.2.2. GFU Technical Constraints

• Power Generation

The power generation of GFU is limited by maximum and minimum values, which are indicated in (6). Moreover, to prevent setting values in off-times, the binary variable I_t^{GF} is defined.

$$P_t^{GF,Min} I_t^{GF} \leq P_t^{GF} \leq P_t^{GF,Max} I_t^{GF} \quad (6)$$

• Ramping Up/Down

Ramping up and ramping down in producing power of GFU between two consecutive hours are defined as (7) and (8), respectively, in which the binary decision variables, i.e., X_t , Y_t are obtained based on a unit commitment in the scheduling period. Otherwise, these binary variables are starting-up and shutting-down indicators defined as (9) and (10), respectively.

$$P_t^{GF} - P_{t-1}^{GF} \leq (1 - X_t) R^{up} + X_t P_t^{GF,Min} \quad (7)$$

$$P_{t-1}^{GF} - P_t^{GF} \leq (1 - Y_t) R^{dn} + Y_t P_t^{GF,Min} \quad (8)$$

$$X_t - Y_t = I_t^{GF} - I_{t-1}^{GF} \quad (9)$$

$$X_t + Y_t \leq 1 \quad (10)$$

• Minimum Up/Down Time

GFUs cannot start-up and shutdown in each hour that we want to commit. Therefore, linearized minimum uptime and minimum downtime of units should be considered as (11)–(14) and (15)–(18), respectively.

$$UT = \text{Max}\{0, \text{Min}(N_T, (T^{ON} - IS_{t=0}^{ON}) I_{t=0}^{GF})\} \quad (11)$$

$$\sum_{t=1}^{UT} (1 - I_t^{GF}) = 0 \quad ; \quad \forall t = 1, \dots, UT \quad (12)$$

$$\sum_{t'=t}^{t+T^{ON}-1} I_{t'}^{GF} \geq T^{ON} \times X_t \quad ; \quad \forall t = UT + 1, \dots, N_T - T^{ON} + 1 \quad (13)$$

$$\sum_{t'=t}^{UT} (I_{t'}^{GF} - X_t) \geq 0 \quad ; \quad \forall t = N_T - T^{ON} + 2, \dots, N_T \quad (14)$$

$$DT = \text{Max}\{0, \text{Min}(N_T, (T^{\text{OFF}} - IS_{t=0}^{\text{OFF}})(1 - I_{t=0}^{\text{GF}}))\} \quad (15)$$

$$\sum_{t=1}^{DT} I_t^{\text{GF}} = 0 \quad ; \quad \forall t = 1, \dots, DT \quad (16)$$

$$\sum_{t'=t}^{t+T^{\text{OFF}}-1} (1 - I_{t'}^{\text{GF}}) \geq T^{\text{OFF}} \times Y_t \quad ; \quad \forall t = DT + 1, \dots, N_T - T^{\text{OFF}} + 1 \quad (17)$$

$$\sum_{t'=t}^{DT} (1 - I_{t'}^{\text{GF}} - Y_t) \geq 0 \quad ; \quad \forall t = N_T - T^{\text{OFF}} + 2, \dots, N_T \quad (18)$$

• Gas Fuel Consumption

Gas fuel function reported in the second term of (3) is defined as Equation (19) in which the power produced by GFU follows gas consumption and is restricted by the maximum allowed daily gas consumption, which is stated as (20).

$$F^{\text{GF}}(P_t^{\text{GF}}) = aP_t^{\text{GF}} + b \quad (19)$$

$$\sum_{t=1}^{NT} \left(F^{\text{GF}}(P_t^{\text{GF}}) - \sum_{k=1}^{NGS} G_{k,t}^{\text{dis,GSS}} \right) \leq G^{\text{Max,daily}} \quad (20)$$

• Maximum Allowed Sold Power

The dispatched power of WPU, and also the generated power of GFU, could be sold to the energy market by the transmission line, which is depicted in (21). This means that, according to their nominal capacities, each facility could generate maximum allowed power to transmit.

$$P_t^{\text{WT}} + P_t^{\text{GF}} \leq P^{\text{TMax}} \quad (21)$$

4.2.3. P2G Technology Constraints

The non-dispatched power of WPU, i.e., curtailed electric power of WPU, is transferred to the P2G technology to produce gas fuel for GFUs, which have gas-consumption limitations. Thus, Equation (22) states that the rest of WPU's power, as consumed P2G's power, is produced by the SNG with the coefficient conversion efficiency, i.e., η^{P2G} . In addition, the consumed power of P2G technology is limited by (23). Moreover, the difference between dispatched, i.e., sold power to energy market, and forecasted power of WPU is utilized in the P2G conversion facility, as represented in Constraint (24).

$$\eta^{\text{P2G}} P_{p,t}^{\text{P2G}} = G_{p,t}^{\text{P2G}} = G_{k,t}^{\text{ch,GSS}} \quad (22)$$

$$P_{p,t}^{\text{P2G,Min}} I_t^{\text{P2G}} \leq P_{p,t}^{\text{P2G}} \leq P_{p,t}^{\text{P2G,Max}} I_t^{\text{P2G}} \quad (23)$$

$$P_t^{\text{WT}} + P_{p,t}^{\text{P2G}} \leq P_t^{\text{FWT}}(v_t^{\text{WT}}) \quad (24)$$

4.2.4. GSS Technical Constraints

The gas produced by P2G, which is equivalent to the charging gas of GSS, is restricted to minimum and maximum values of the charging mode, according to (25). Likewise, for the discharging mode of GSS, a similar constraint to (25) is defined as (26). To avoid simultaneously charging and discharging modes in GSS, constraint (27) is applied. The state of charge (SoC) of GSS is calculated through Equation (28) by considering charged and discharged gas. Furthermore, the SoC of GSS is specified

with corresponding values by (29). Analogous to the other energy storages, the SoC level of GSS at the end of the scheduling period must be equal to the initial value of storage indicated by (30).

$$G^{ch,GSS,Min} I_t^{ch,GSS} \leq G_{k,t}^{ch,GSS} \leq G^{ch,GSS,Max} I_t^{ch,GSS} \quad (25)$$

$$G^{dis,GSS,Min} I_t^{dis,GSS} \leq G_{k,t}^{dis,GSS} \leq G^{dis,GSS,Max} I_t^{dis,GSS} \quad (26)$$

$$I_t^{ch,GSS} + I_t^{dis,GSS} \leq 1 \quad (27)$$

$$A_t^{GSS} = A_{t-1}^{GSS} + \eta^{ch,GSS} G_{k,t}^{ch,GSS} - \frac{G_{k,t}^{dis,GSS}}{\eta^{dis,GSS}} \quad (28)$$

$$A^{Min} \leq A_t^{GSS} \leq A^{Max} \quad (29)$$

$$A_{t=0}^{GSS} = A_{t=NT}^{GSS} \quad (30)$$

4.3. Robust Optimization Method

Electricity price as an uncertain and unpredictable parameter is alleviated with the RO method, which gives the authority to the operator to choose how much the risk that the operator wants to take. The general form of the optimization problem is provided by (31).

$$\begin{aligned} \min & \sum_i f(x_i) + \sum_j d_j \cdot x_j \\ \text{s.t.} & \\ & h_1(x) < 0, h_2(x) = 0; x \in \{x_i, x_j\} \end{aligned} \quad (31)$$

d_j is a parameter between an upper bound and a lower bound. x_i and x_j are continuous and binary decision variables, respectively. The RO method can be formulated as follows:

$$\min \left\{ \sum_i f(x_i) + \sum_j d_j^{\min} \cdot x_j + \max_{\{j||j| \leq \Gamma\}} \left\{ \sum_j (d_j^{\max} - d_j^{\min}) \cdot x_j \right\} \right\} \quad (32)$$

$\Gamma \in [0, N_j]$ is an integer variable and defines the system's conservatism level according to the electricity-market-price uncertainty. In fact, this variable leads to obtain more reliable and acceptable results. Equation (32) is a complex problem to solve; thus, the Equation can be formulated as follows:

$$\min \left\{ \sum_i f(x_i) + \sum_j d_j^{\min} \cdot x_j + \max_{\sum_j W \leq \Gamma, 0 \leq W \leq 1, x_j \leq m_j} \left\{ \sum_j (d_j^{\max} - d_j^{\min}) \cdot m_j \cdot w \right\} \right\} \quad (33)$$

Using strong duality theory, the min-max problem of (33) can be changed to a single minimization problem.

$$\min \left\{ \sum_i f(x_i) + \sum_j d_j^{\min} \cdot x_j + \alpha \cdot \Gamma + \sum_j \beta_j \right\} \quad (34)$$

$$\alpha + \beta_j \geq (d_j^{\max} - d_j^{\min}) \cdot m_j \quad (35)$$

$$\beta_j \geq 0 \quad j = 1 : N_j \quad (36)$$

$$m_j \geq 0 \quad j = 1 : N_j \quad (37)$$

$$\alpha \geq 0 \quad (38)$$

$$x_j \leq m_j \quad j = 1 : N_j \quad (39)$$

The objective function of (3) is a max problem, which can be reformulated as a min problem, as follows:

$$\Phi = \text{Min} \left\{ - \sum_{t=1}^{NT} \left(\begin{aligned} & \lambda_t^E (P_t^{WT} + P_t^{GF}) - \lambda_t^G (F_t^{GF} (P_t^{GF})) \\ & - \sum_{k=1}^{NGS} [C_{k,t}^{ch,GSS} (G_{k,t}^{ch,GSS}) + C_{k,t}^{dis,GSS} (G_{k,t}^{dis,GSS})] \\ & - \sum_{p=1}^{NP} [C_{p,t}^{P2G} (G_{p,t}^{P2G})] \end{aligned} \right) \right\} \quad (40)$$

The objective function of (40) is a deterministic problem, and uncertainty is not considered. To handling the uncertainty, the RO method can be applied to the objective function of (40), as shown below:

$$\text{Min} \left\{ - \sum_{t=1}^{NT} \left(\begin{aligned} & \lambda_t^E (P_t^{WT} + P_t^{GF}) - \lambda_t^G (F_t^{GF} (P_t^{GF})) \\ & - \sum_{k=1}^{NGS} [C_{k,t}^{ch,GSS} (G_{k,t}^{ch,GSS}) + C_{k,t}^{dis,GSS} (G_{k,t}^{dis,GSS})] \\ & - \sum_{p=1}^{NP} [C_{p,t}^{P2G} (G_{p,t}^{P2G})] + \beta_t \end{aligned} \right) \right\} + \alpha \cdot \Gamma \quad (41)$$

$$\alpha + \beta_t \geq (\lambda_t^{E,\max} - \lambda_t^{E,\min}) \cdot m_t \quad (42)$$

$$\beta_t, \alpha, m_t \geq 0 \quad (43)$$

$$P_t^{E,sell} \leq m_t \quad (44)$$

$$P_t^{E,sell} = P_t^{WT} + P_t^{GF} \quad (45)$$

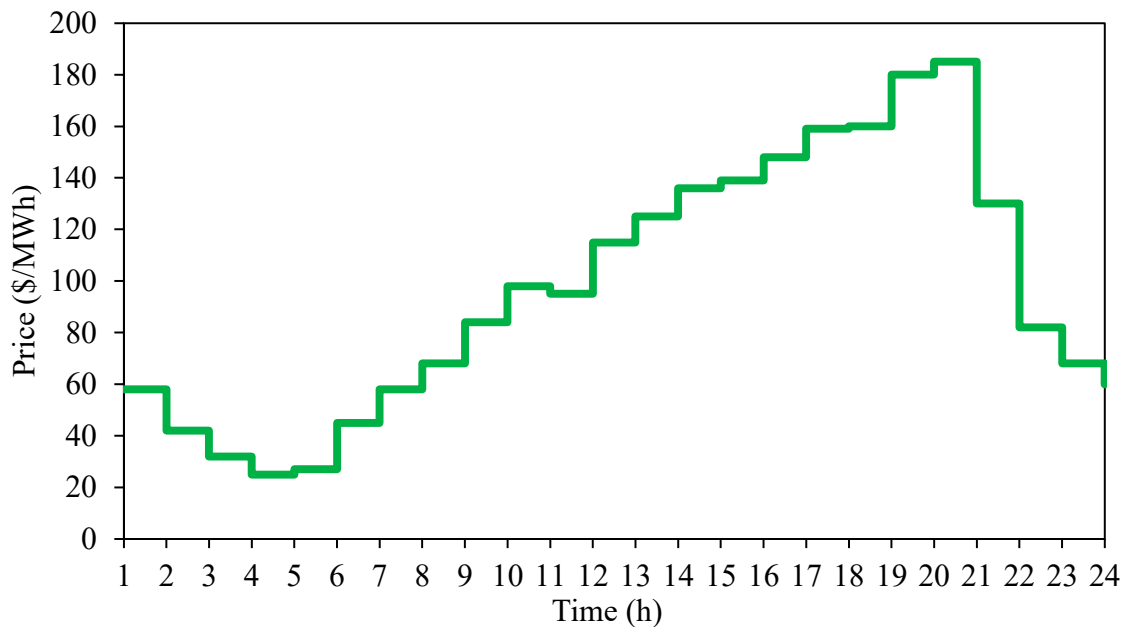
5. Case Studies

5.1. Test System and Data

The proposed bidding strategy of GFUs in the presence of P2G conversion technology and WPU is modeled as a mixed-integer linear programming (MILP) problem. Therefore, this optimization problem was solved by utilizing CPLEX 12.9 solver in GAMS 27.3 on a laptop with an Intel Core i7 processor with 2.50 GHz and 8 GB of RAM. As indicated before, the presented hybrid energy system consists of a GFU, a WPU, P2G conversion technology, and GSS facilities; the limitation of daily gas fuel consumption is considered, as well. All required parameters of the given equipment are reported in Table 2. The electricity day-ahead market price is shown in Figure 3, and the price of natural gas is about 2.9 \$/MBtu. The operation costs of the P2G facility and GSS unit are taken from References [15,26]. The maximum operating capacity of the transmission line between the hybrid energy system and the energy market is 150 MW, and the maximum allowed daily gas fuel consumption by GFUs is 13,955.640 MBtu [12,52]. The nominal capacity of WPU is precisely 180 MW; the other technical parameters are depicted in Table 3. The forecasted WPU, along with dispatchable power and analysis of them, is provided in Section 4.2.

Table 2. Required parameters of GFU, P2G, and gas storage system (GSS) facilities [15].

| GFU Facility | | GSS Facility | | P2G Facility | |
|--------------------------------|--------|--------------------------------|--------|----------------------------------|--------|
| Parameters | Values | Parameters | Values | Parameters | Values |
| $p_{GF,Min}^{GF} \text{ (MW)}$ | 20 | $\eta^{ch,GSS} \text{ (\%)}$ | 0.8 | $\eta^{P2G} \text{ (\%)}$ | 0.8 |
| $p_{GF,Max}^{GF} \text{ (MW)}$ | 100 | $\eta^{dis,GSS} \text{ (\%)}$ | 1 | $p_{P2G,Min}^{P2G} \text{ (MW)}$ | 5 |
| $T^{ON} \text{ (h)}$ | 3 | $G^{ch,GSS,Min} \text{ (MW)}$ | 5 | $p_{P2G,Max}^{P2G} \text{ (MW)}$ | 30 |
| $T^{OFF} \text{ (h)}$ | 3 | $G^{ch,GSS,Max} \text{ (MW)}$ | 30 | | |
| $IS_{t=0}^{ON} \text{ (h)}$ | 0 | $G^{dis,GSS,Min} \text{ (MW)}$ | 5 | | |
| $IS_{t=0}^{OFF} \text{ (h)}$ | 2 | $G^{dis,GSS,Max} \text{ (MW)}$ | 30 | | |
| $R^{up} \text{ (MW/h)}$ | 30 | $A^{Min} \text{ (MWh)}$ | 0 | | |
| $R^{dn} \text{ (MW/h)}$ | 30 | $A^{Max} \text{ (MWh)}$ | 100 | | |
| $a \text{ (MBtu/MWh)}$ | 10 | | | | |
| $b \text{ (MBtu/h)}$ | 2 | | | | |

**Figure 3.** The forecasted electricity market price [51].**Table 3.** Technical parameters of WPU facility [26].

| Parameters | $v^{CI} \text{ (m/s)}$ | $v^{CO} \text{ (m/s)}$ | $v^{WT,R} \text{ (m/s)}$ | $P^{WT,R} \text{ (MW)}$ |
|------------|------------------------|------------------------|--------------------------|-------------------------|
| Values | 3 | 25 | 11 | 180 |

5.2. Simulation and Analysis of Results

In this subsection, we investigate the proposed bidding strategy to the day-ahead energy market, with two case studies that are studied and analyzed. It should be mentioned that the gas-fuel consumption of GFUs is limited and the application of P2G conversion technology has solved this limitation to produce the electric power by GFUs without any reduction in their gas consumption. Therefore, these simulation processes have been categorized into two different cases. Case 1 indicates that the bidding strategy problem is investigated with GFU and WPU facilities, along with the limitation constraint of natural-gas consumption. However, in Case 2, introducing and applying P2G technology coupled with the two mentioned facilities produces more electric power from GFU by converting extra

wind power to natural gas. These two cases are briefly denoted as follows. Finally, a risk management methodology based on a robust approach is implemented to the presented optimization problem.

1. Determining the bidding strategy of GFU and WPU by considering the gas-fuel-consumption limitation.
2. Determining the bidding strategy of coupled GFU-P2G-WPU facilities by considering the gas-fuel-consumption limitation.

Case 1. In this case, two states of GFU's power production with and without limitation of gas fuel consumption are considered. These situations affect the whole obtained profit by the introduced hybrid system and the imported gas. At first, the dispatched power of GFU is shown in Figure 4. It should be noted that the foremost priority to dispatch is the free energy of WPU. Then the remaining capacity of the transmission line will be filled with optimal power dispatch of GFU. In the situation of gas-fuel limitation, the sold power to the energy market in high price hours (i.e., hours 19–21) is equal to the maximum capacity of the transmission line. Thus, when this limitation is removed, GFU's generated power in the medium price hours (i.e., hours 15–18) increases to reach the maximum value of the transmission line, depicted in Figure 4. Moreover, as can be observed in this figure, the generated power in the presence of gas-fuel limitation in hour 15 is less than the power in status without any restriction, which is due to the limitations of transmission line capacity and gas fuel. The generation of GFU mainly depends on the electricity price and wind power. During hours 5–12, GFU is offline due to low electricity prices and high wind-power penetration. However, during initial hours and after hour 12, since wind power reduces and the transmission line's capacity is empty, the GFU is online. Until hour 21, the GFU still online and at the final hours is getting offline due to a reduction in electricity price and an increase in wind power. In Figure 5, the forecasted and dispatched power of WPU are illustrated. As shown in Figure 5, there is a non-dispatched power during hours 5, 7, 9–10, 12–13, and 22–23 because of transmission-line-capacity limitations. However, utilizing free and green energy wind power is so important from both environmental and economic aspects. Thus, in this work, P2G technology is proposed and evaluated in Case 2, to solve this issue. In these two defined situations of gas limitations, the imported natural gas from the upstream gas network is clarified in Figure 6. As can be seen, the pattern of the purchased gas corresponds to the GFU's generation. This is because the GFU is the only gas demander in the system, so when the GFU is online, the required amount of gas is purchased from the market. The considerable point in this figure occurred at hours 15–17. In this period, the GFU wants to reach the maximum capacity because of the high electricity price, and, as a result, it requires more fuel, but the amount of purchased gas is limited due to the fuel limitations. Therefore, this limitation impacts the GFU generation and prevents it from reaching the maximum capacity.

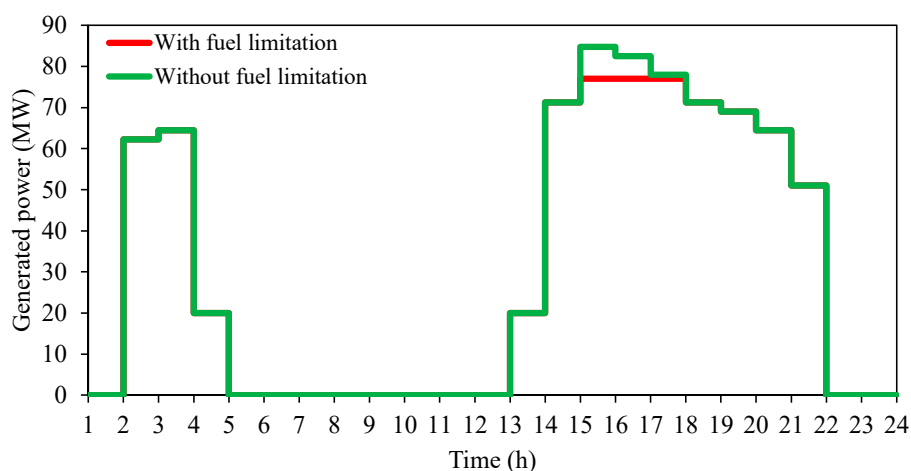


Figure 4. The generated power of GFU in Case 1 with two states.

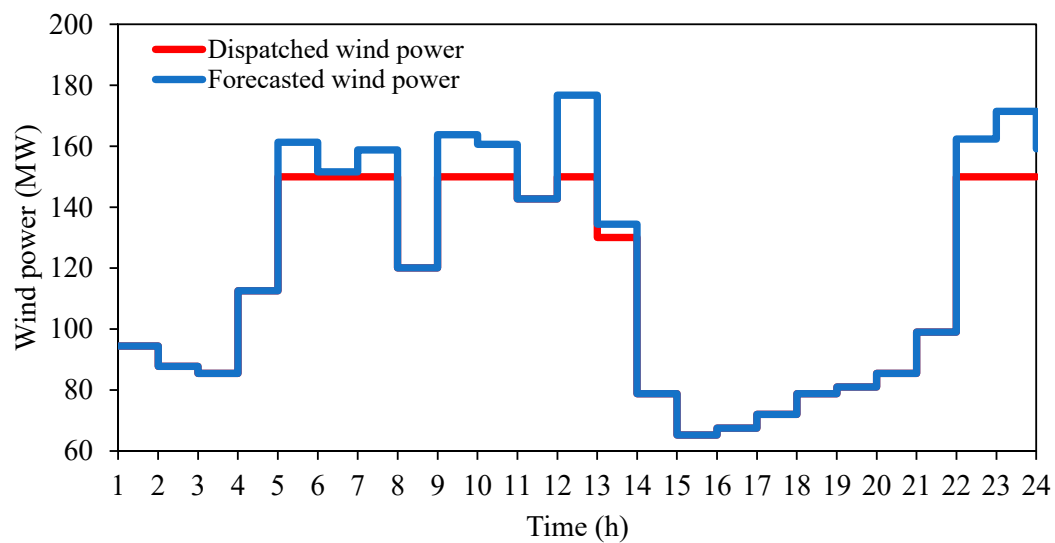


Figure 5. The forecasted and dispatched powers of WPU in Case 1.

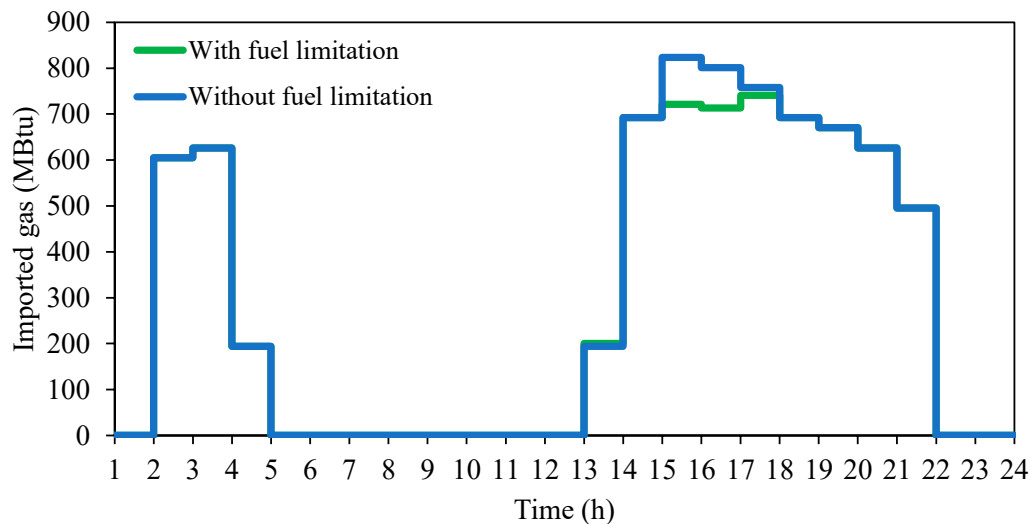


Figure 6. The imported natural gas from the upstream network in Case 1 with two states.

Case 2. To solve the curtailed and non-dispatched power of WPU that has been occurred in Case 1, P2G conversion technology is applied as illustrated following figures. In reality, by this deployment, the GFU's gas-fuel limitation will be removed, and the hybrid energy system could obtain higher profit by selling power to the day-ahead energy market. Thus, in Figure 7, the comparison of the dispatched power of WPU for Case 1 and Case 2 is indicated. According to the figure, the amount of curtailed power owing to transmission-line capacity is dispatched in this case, using the P2G facility. During hours 5, 7, 9–10, and 12–13, wind power is converted to gas, as depicted in Figure 8. The GSS during these hours is charged, and, during the high-electricity-price period, i.e., hours 15–17, it is discharged to supply the GFU. In doing so, according to Figure 9, increasing the generated power of GFU resulted via the operation of discharged natural gas by GSS, and the gas-fuel restriction is eliminated, similar to Case 1, in the state of without gas limitation. Decreasing the GFU's generation at peak hours of the electricity price occurs due to the increasing wind power generation and the restriction of transmission line capacity.

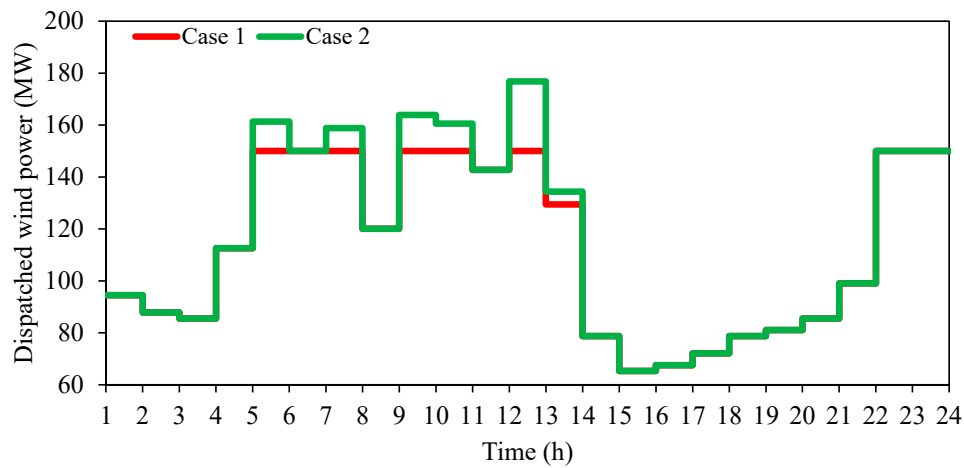


Figure 7. The comparison of dispatched power of WPU for Case 1 and Case 2.

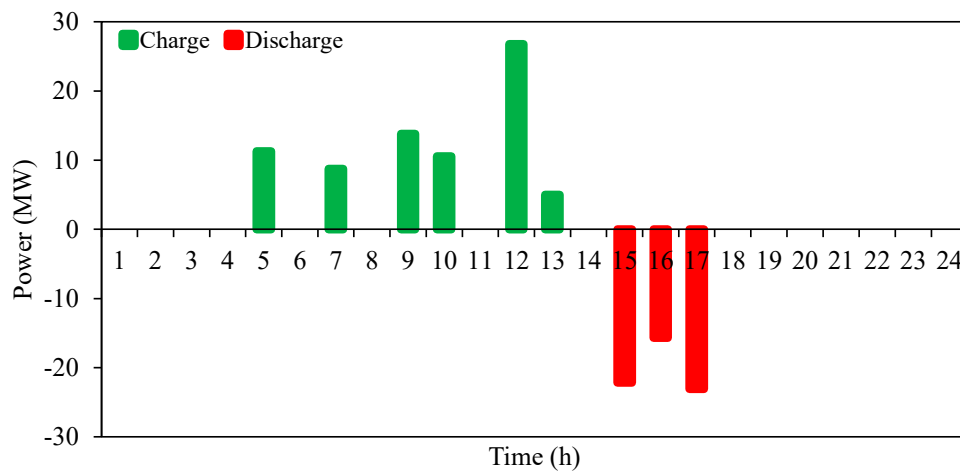


Figure 8. Charging and discharging status of the GSS.

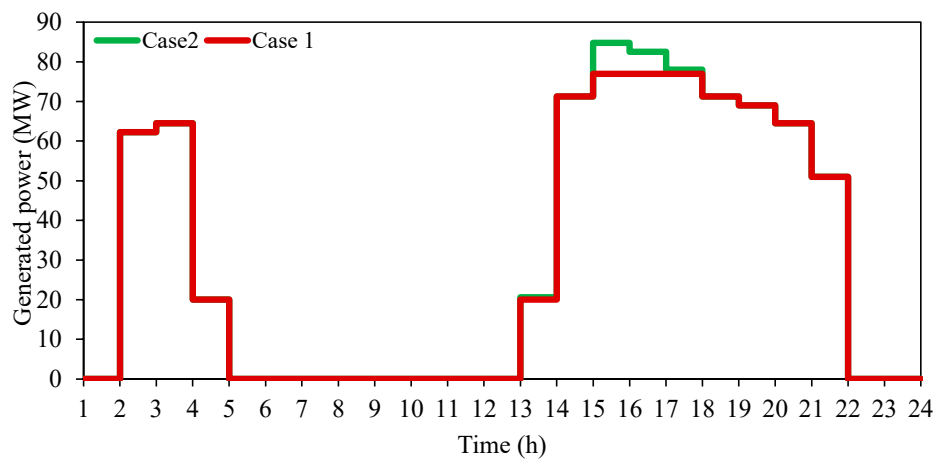


Figure 9. The generated power of GFU for each two cases.

Table 4, in the following, analyzes the all achieved profit and purchased natural gas values for two different case studies in the whole time horizon, i.e., 24 h ahead. Only the purchased natural gas in the status without gas-fuel limitation for the two cases besides reporting the related profits is provided in Table 4. As shown in Table 4, the hybrid energy system's maximum profit and the minimum purchased

natural gas are constructed via Case 2. It is noticeable that the achieved profit in Case 2 is equal in the two statuses of with/without gas-fuel limitation.

Equation

Table 4. The comparison of profit and purchased natural gas in Case 1 and Case 2.

| Cases | Profit (\$) | | Purchased Natural Gas (MBtu) |
|--------|---------------------|------------------------|------------------------------|
| | With Gas Limitation | Without Gas Limitation | |
| Case 1 | 318,710.5 | 320,353.6 | 14,357.7 |
| Case 2 | 320,944.9 | 320,944.9 | 14,080.9 |

At the end of this section, we applied the proposed robust approach to the bidding strategy of the hybrid energy system, and so the results are introduced as follows: For different uncertainty budgets of electricity market price, various day-ahead electricity price profiles are calculated, which are demonstrated in Figure 10. Applying robust optimization cause a reduction in the electricity price for the worst-case hours. In other words, whatever the uncertainty budget is increased, the optimization problem is moved through a pessimistic path and get a more robustness level in decisions. For instance, $\Gamma = 6$ means uncertainty is considered for six worst-case hours, i.e., $t = 15\text{--}20$, and during this period, electricity price is decreased. Moreover $\Gamma = 0$ means that uncertainty is not considered and the problem is deterministic, while $\Gamma = 24$ indicates the uncertainty is considered for the whole scheduling time horizon and it is the most conservative condition. Besides, the GFU's dispatch is not changed for the lower uncertainty budget, i.e., $\Gamma = 0, 6, 12, 18$ affecting the GFU's generation as depicted in Figure 11. Moreover, robust optimization affects the GSS charging and discharging policy for different uncertainty budgets. This is occurred due to the decrease in electricity prices in worst-case hours. Likewise, all levels of uncertainty budget are the same effect on the SoC of the GSS unit reported in Figure 12. However, the SoC of the GSS unit in the deterministic approach, i.e., $\Gamma = 0$ is different from other uncertainty budgets. Table 5 reveals the impacts of uncertainty budget on the whole decreasing profit of the system due to the adopting more conservative behavior in the uncertain energy market. Furthermore, in order to investigate the impacts of uncertainty budget and also electricity price deviations on the obtained profit of the hybrid energy system, Figure 13 is delineated the relevant results on the proposed maximization problem. According to the figure, price deviation and uncertainty budget have similar effects on the profit and the more price deviation and uncertainty budget increase, the more reduction in the profit can be seen.

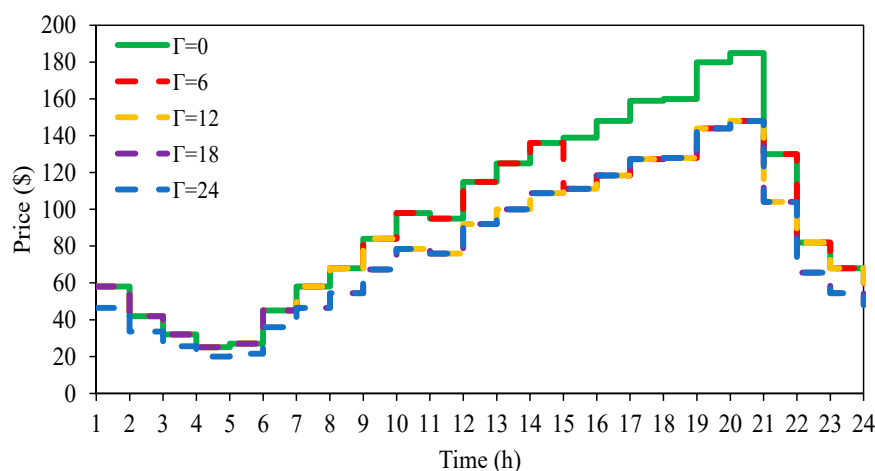


Figure 10. The uncertainty budget of day-ahead electricity market price.

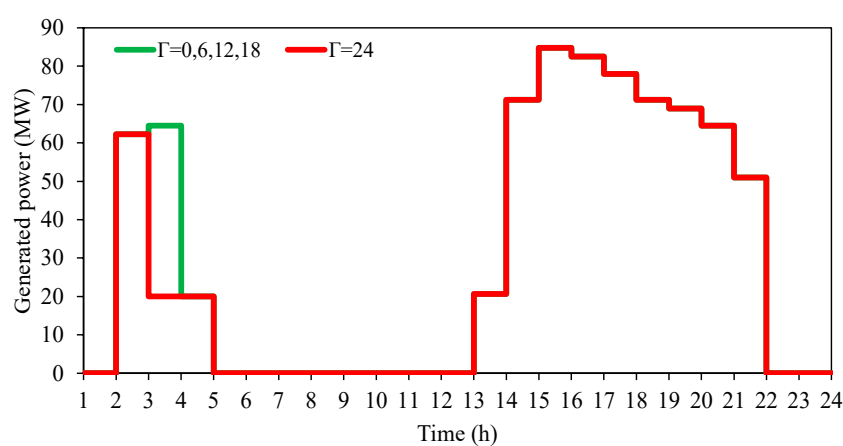


Figure 11. The effect of the uncertainty budget on dispatching power of GFU.

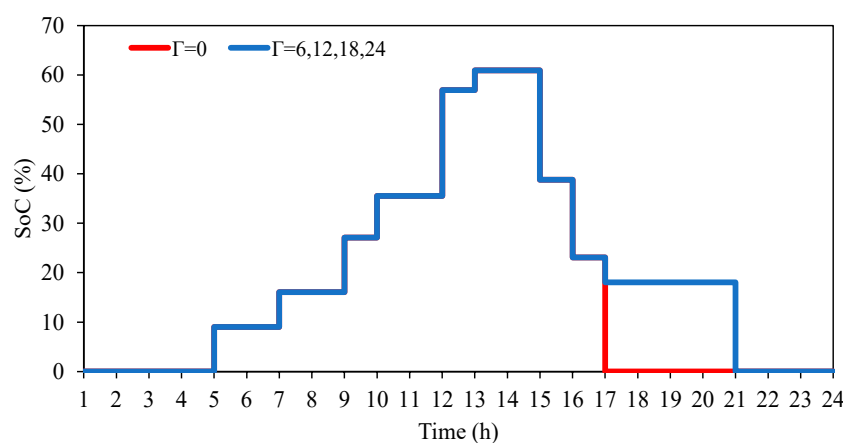


Figure 12. The effect of the uncertainty budget on the state of charge (SoC) of GSS.

Table 5. Effects of uncertainty budget on obtaining profit in Case 2.

| Uncertainty Budget | | $\Gamma=0$ | $\Gamma=6$ | $\Gamma=12$ | $\Gamma=18$ | $\Gamma=24$ |
|--------------------|-------------|------------|------------|-------------|-------------|-------------|
| Case 2 | | | | | | |
| | Profit (\$) | 320,944.9 | 291,814.9 | 270,982.8 | 258,789.998 | 252,783.5 |

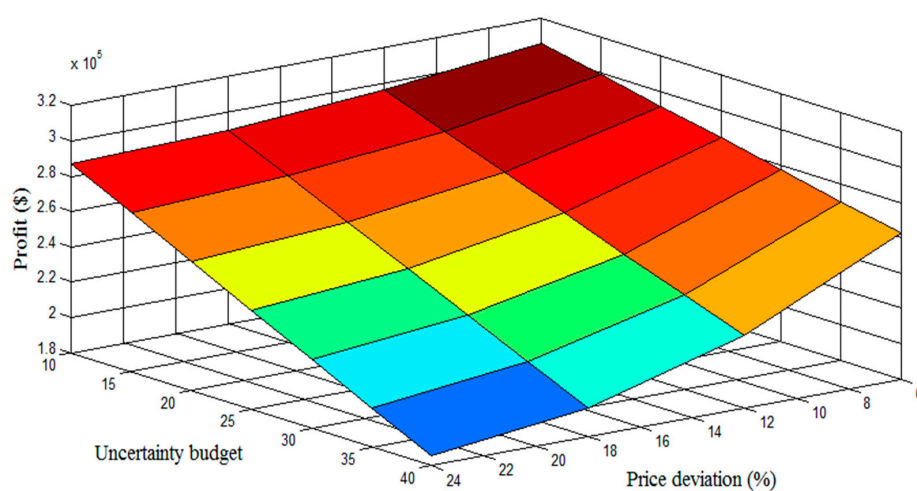


Figure 13. Illustration of price deviation and uncertainty budget on obtained profit.

6. Discussion

According to the natural-gas-fuel-consumption limitations globally and the full utilization of WPU's predicted power, a hybrid energy system was proposed in this paper. The curtailed and non-dispatched power of WPU was solved via the installation of P2G technology. It could be stated that the extra wind power, which is not dispatched due to the transmission line capacity, was converted to natural gas through the P2G procedure. Thus, the generated natural gas stored in GSS units was discharged to supply the input energy of GFUs. The results verify that the whole obtained profit was increased by applying the proposed system in which the total profit is equal to the without-gas fuel-limitation status. In addition, the purchased natural gas was decreased compared to the single energy system (i.e., without consideration of P2G facility), along with providing the full usage of WPU. The robust optimization method was then added to the system's optimal operation strategy to actualize the process. With this approach, the system operator has the ability to choose how much risk needs to be taken. As with the electricity market uncertainty investigation, lower obtained profit happens at the higher uncertainty budget, and the higher obtained profit occurs at the lower uncertainty budget.

7. Conclusions

In this paper, a robust optimal operation strategy of a hybrid energy system, consisting of a gas-fired unit (GFU), power-to-gas (P2G) facility, and wind power unit (WPU) for the day-ahead energy market, was proposed. The proposed energy system has limitations in fuel purchasing and selling power. The wind power is still non-dispatched because of transmission-line limitation, and also the GFU cannot reach its maximum capacity during high-electricity-price periods, due to fuel limitation. The proposed P2G technology assists the energy system in solving these issues. During high-wind-penetration hours, the excess of wind power that cannot be exported converts to gas and is stored at the gas storage system (GSS). Then, during high-electricity-price hours, GSS discharges to supply the GFU. In doing so, the profit of the presented hybrid energy system increases by nearly 1%. As indicated in numerical results, the contribution of P2G conversion technology is marked as backup facilities in providing required natural gas for GFUs, which have limitations in gas fuel consumption. It can also be stated that the curtailed and non-dispatched power of WPU is utilized as consumed power by the P2G facility, to contribute GFUs more actively in proposing their bids into the energy market. Finally, to investigate the market price uncertainty in obtaining maximum profit, robust optimization was performed to manage the uncertainty. The presented robust model is based on the uncertainty budget, and the amount of risk can be controlled. Increasing the risk by adjusting a higher uncertainty budget causes a decrease in electricity price and, consequently, obtained profit. Considering the price uncertainty for the whole time horizon, i.e., 24 h, it was reduced by about 22% in the profit. As a result, getting more robustness levels will lead to a lower profit of the system. Furthermore, the current research can be extended by considering the upstream power grid and natural gas network constraints with more details. In addition, the impact of P2G technology can be investigated in different multiple-energy-carrier systems, such as energy hubs, multi-carrier microgrids, etc. Moreover, other associated uncertainties can be taken into account, and their effect can be evaluated.

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Nomenclature

Indices:

| | |
|-----|-----------------------------|
| t | Index of time |
| p | Index of P2G technologies |
| k | Index of gas storage system |

Parameters:

| | |
|------------------------------------|---|
| λ_t^E | Electricity market price (\$/MWh) |
| λ_t^G | Natural gas market price (\$/MBtu) |
| $C_{k,t}^{ch,GSS}$ | Cost of charging GSS k at time t (\$/MBtu) |
| $C_{k,t}^{dis,GSS}$ | Cost of discharging GSS k at time t (\$/MBtu) |
| $C_{p,t}^{P2G}$ | Cost of producing SNG by P2G technology p at time t (\$/MBtu) |
| v_{CI} | Cut-in speed data of WPU (m/s) |
| v_{CO} | Cut-out speed data of WPU (m/s) |
| v_t^{WT} | Wind speed data of WPU at time t (m/s) |
| $v_{WT,R}$ | Rated wind speed of WPU (m/s) |
| $P_{WT,R}$ | Rated power of WPU (MW) |
| $P_t^{FWT}(v_t^{WT})$ | Forecasted power of WPU at time t (MW) |
| $P_{GF,Max}, P_{GF,Min}$ | Maximum and minimum generated power of GFU (MW) |
| a | Linear cost coefficient of GFU (MBtu/MWh) |
| b | No-load cost of GFU (MBtu/h) |
| $G^{Max,daily}$ | Maximum daily gas fuel consumption by GFU (MBtu) |
| T^{ON}, T^{OFF} | Minimum up-time and down-time of GFU (h) |
| $IS_{t=0}^{ON}, IS_{t=0}^{OFF}$ | Initial on/off status of GFU |
| $P_{T,Max}$ | Maximum capacity of the transmission line (MW) |
| η^{P2G} | P2G technology efficiency (%) |
| R^{up}, R^{dn} | Ramp-up and ramp-down of GFU (MW/h) |
| $\eta^{ch,GSS}, \eta^{dis,GSS}$ | Charging and discharging gas efficiencies of GSS (%) |
| $G^{ch,GSS,Min}, G^{ch,GSS,Max}$ | Minimum and maximum charging gas of GSS (MW) |
| $G^{dis,GSS,Min}, G^{dis,GSS,Max}$ | Minimum and maximum discharging gas of GSS (MW) |
| A^{Min}, A^{Max} | Minimum and maximum capacity of GSS (MWh) |
| $p_{P2G,Min}, p_{P2G,Max}$ | Minimum and maximum power consumption of P2G technology (MW) |

Variables:

| | |
|---------------------------------------|--|
| UT, DT | Up-time and down-time of GFU (h) |
| X_t, Y_t | Start-up and shutdown binary variables of GFU at time t |
| P_t^{GF} | Power generated of GFU at time t (MW) |
| $G_{k,t}^{ch,GSS}, G_{k,t}^{dis,GSS}$ | Charging and discharging gas of GSS k at time t (MW) |
| $G_{p,t}^{P2G}$ | Gas production of P2G technology p at time t (MW) |
| $p_{p,t}^{P2G}$ | Power consumption of P2G technology p at time t (MW) |
| I_t^{GF} | On/off status binary variables of GFU at time t |
| p_t^{WT} | Dispatched power of WPU at time t (MW) |
| A_t^{GSS} | Capacity of GSS at time t (MWh) |
| $I_t^{ch,GSS}, I_t^{dis,GSS}$ | Charging and discharging binary variables of GSS at time t |
| I_t^{P2G} | On/off status binary variables of P2G technology at time t |

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